

Final report to the
National Aeronautics and Space Agency (NASA)

for

NASA grant NAG1-1830

Entitled

“Cloud Statistics for NASA Climate Change Studies”

dates

18 April 1996 – 17 April 1999

from

The University of Wisconsin-Madison
Space Science and Engineering Center
1225 West Dayton Street
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written by

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ACCOMPLISHMENTS:

The Principal Investigator participated in two field experiments and developed a global data set on cirrus cloud frequency and optical depth to aid the development of numerical models of climate. Four papers were published under this grant. An outline of the accomplishments is:

SUCCESS (SUBsonic aircraft: Contrail & Cloud Effects Special Study) - The Principal Investigator aided weather forecasters in the start of the field program. A paper also was published (Wylie, Santek, and Starr, J. Appl. Meteor., April, 1998) on the clouds of one day studied in SUCCESS and the use of the satellite stereographic technique to distinguish cloud forms and heights of clouds.

SHEBA (Surface Heat Budget in the Arctic) FIRE/ACE (Arctic Cloud Experiment) - The Principal Investigator provided weather and cloud forecasts for four research aircraft crews, NASA's ER-2, UCAR's C-130, University of Washington's Convair 580, and the Canadian Atmospheric Environment Service's Convair 580. Forecasts were issued daily from April 6 to July 30. Approximately 105 forecasts were written. However, only 95 are recorded in the FIRE/ACE web page because the forecasts began before the FIRE/ACE web page came on line. In addition to the forecasts, the Principal Investigator made daily weather summaries with calculations of air trajectories for 54 flight days in the experiment. The trajectories show where the air sampled during the flights came from and will be used in future publications to discuss the origin and history of the air and clouds sampled by the aircraft. All of these weather summaries and trajectories are publicly displayed on the Principal Investigator's web page, <http://www.ssec.wisc.edu/~donw>, to which the FIRE/ACE web page is linked (<http://eosweb.larc.nasa.gov/ACEDOCS/index.htm>). A paper discussing the how well the FIRE/ACE data represent normal climatic conditions in the arctic is being prepared.

The Principal Investigator's web page became the source of information for weather forecasting by the scientists on the SHEBA ship. Other plots of model forecast fields did not cover the arctic basin. This web page was operated before the FIRE/ACE flights and was kept running for the remainder of the SHEBA period after the FIRE/ACE flights. The Principal Investigator's weather and cloud forecasts also were transmitted to the SHEBA ship during the FIRE/ACE flights.

Global Cirrus frequency and optical depth - a continuing analysis of global cloud cover and frequency distribution are being made from the NOAA polar orbiting weather satellites. This analysis is sensitive to cirrus clouds because of the radiative channels used. During this grant three papers were published which describe cloud frequencies, their optical properties and compare the Wisconsin HIRS Cloud Analysis to other global cloud data such as the International Satellite Cloud Climatology Program (ISCCP) and the Stratospheric Aerosol and Gas Experiment (SAGE). These comparisons show that the largest cloud program, the ISCCP, has under reported cirrus clouds by about 15%, while the most sensitive instrument, SAGE, indicates very thin cirrus are nearly continuously present at high altitudes in the tropics. The HIRS provides more cloud observations than the SAGE because of the instrument's design and operation. A summary of eight years of HIRS data will be published in the J. of Climate in late 1998. Important information from this study are: 1) cirrus clouds cover most of the earth, 2) they are found about 40% of the time globally, 3) in the tropics cirrus cloud frequencies are even higher, from 80-100%, 4) there is slight evidence that cirrus cloud cover is increasing in the northern hemisphere at about 0.5% per

year, and 5) cirrus clouds have an average infrared transmittance of about 40% of the terrestrial radiation.

Global Cloud Frequency Statistics published on the Principal Investigator's web page (<http://www.ssec.wisc.edu/~donw>) have been used in the planning of the future CRYSTAL experiment and have been used for refinements of a global numerical model operated at the Colorado State University.

PAPER PUBLISHED:

Wylie, D. P., and Pi-Huan Wang, 1997: Comparison of cloud frequency data from the high-resolution infrared radiometer sounder and the Stratospheric Aerosol and Gas Experiment II., *J. Geophys. Res.*, **102**, 29,893-29,900.

Wylie, D. P., D. Santek, and D. O'C. Starr, 1998: Cloud-top heights from GOES-8 and GOES-9 stereoscopic imagery., *J. Appl. Meteor.*, **37**, 405-413.

Wylie, D. P., and W. P. Menzel, 1999: Eight years of high cloud statistics using HIRS., *J. Climate*, **12**, 170-184.



SPACE SCIENCE AND ENGINEERING CENTER

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*FIRE
NAG-FIRE*

27 October, 1998

Mr. David S. McDougal
NASA LaRC
ASD - Atmospheric Studies Branch
Mail Stop 483
Hampton, VA 23681-0001

Dear Dave:

Enclose is my FIRE-III report along with two view graph for FORM-B: Significant Highlights.
Thank you for the reminder e-mail.

Sincerely,

Donald Wylie

NAGI-1830

Name: Donald Wylie
Institution: University of Wisconsin

TITLE: Cloud Statistics for NASA Climate Change Studies

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instrument's design and operation. A summary of eight years of HIRS data will be published in the J. of Climate in late 1998. Important information from this study are: 1) cirrus clouds cover most of the earth, 2) they are found about 40% of the time globally, 3) in the tropics cirrus cloud frequencies are even higher, from 80-100%, 4) there is slight evidence that cirrus cloud cover is increasing in the northern hemisphere at about 0.5% per year, and 5) cirrus clouds have an average infrared transmittance of about 40% of the terrestrial radiation.

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ABSTRACT from the original proposal (in 1996).

This is a proposal for the participation of Drs. Wylie and Hinton in NASA's FIRE, SUCCESS and SHEBA programs. All three of these programs are studying clouds for the purpose of understanding climate changes. The University of Wisconsin has a 6.5 year record of cloud data collected from weather satellites which can contribute to these programs. In addition, Dr. Wylie also is experienced in aiding NASA research field experiments as a weather forecaster and has access to weather and satellite data through the University of Wisconsin-Madison's McIDAS system. Our contribution to these programs will be:

SUCCESS - will study jet aircraft contrails and their impact on air chemistry and climate. Dr. Wylie will participate in SUCCESS in two ways; 1) He will assist the forecasting team in setting up the field experiment in Salinas KS. Unfortunately he will not be able to be present in Salinas for the entire experiment because of other forecasting commitments to an Air Force cloud research program which starts during the SUCCESS field experiment. 2) Examine the 6.5 year record of cirrus observations taken from the NOAA weather satellites for trends caused by air traffic and other industrial factors. Human impacts on cirrus clouds will be evaluated by comparing areas of air traffic and human population to the uninhabited areas of the world.

SHEBA - Studies of arctic clouds and their impact on radiative heating and cooling. Dr. Wylie also wishes to participate in SHEBA as a weather forecaster during the field exercise. The McIDAS data set will be used as one tool for experiment forecasting operations. Satellite and weather data will be taken in the two years prior to the start of the SHEBA field program to serve as training aids for flight simulation exercises. Cirrus cloud observations also will be made from the NOAA weather satellites during SHEBA as part of the continuing Wisconsin Cloud Climatology. The Wisconsin data can be used to evaluate the infrared radiative effects of the clouds in the middle and upper troposphere. The SHEBA data will also be used to identify biases in the ISCCP and Wisconsin Cloud Climatologies which serve as references for climate model developments.

FIRE-III - the cirrus cloud component. The investigators will participate in development of a Tropical field experiment for FIRE-3. They will use the Wisconsin Cloud Climatology and other data sets archived at UW as references for the expected cloud conditions and variations in areas that are being considered for this field experiment. The applicability of each possible site to the total of the tropics will be assessed with the Wisconsin data.

A study of the impact of recently observed changes in cirrus cloud cover on infrared heating of the upper troposphere will be made from the Wisconsin data set. Data from the Wisconsin lidars will be used to evaluate differences between subtropical and mid-latitude cirrus clouds and the changes in cloud radiative properties caused by cloud microphysical variations.

GOALS:

- A) Provide a global data set on the frequency and optical depth of Cirrus Clouds to serve as a bench mark for the development of numerical models of climate.
- B) Search for time trends in cirrus cloud coverage to aid in the evaluation of climate changes, its causes, and eventual numerical modeling of climate changes.
- C) To assist the Subsonic aircraft: Contrail & Cloud Effects Special Study (SUCCESS) and Surface Heat Budget in the Arctic Arctic Cloud Experiment (SHEBA/ACE) with cloud forecasting and satellite images for planning aircraft missions.

OBJECTIVES:

- 1) Support the weather forecasting and flight operation of SUCCESS (Subsonic aircraft Contrails and Cloud Effects Special Study) in the critical set up phase of the operation.
- 2) Make detailed analyses of cirrus clouds and changes in these clouds in regional areas to evaluate the impact of air traffic and human population on clouds.
- 3) Participate in the SHEBA (Surface Heat Budget in the Arctic) FIRE/ACE (Arctic Cloud Experiment) program as a weather forecaster and provide satellite data.
- 4) Assist FIRE in developing a tropical experiment by studying local, seasonal and inter-annual cloud frequency and changes in cloud frequency in tropical areas.

APPROACH:

The HIRS Cloud Analysis is made from NOAA satellite data sets daily processed by the NOAA Climatic and Environmental Prediction center (NCEP). These data are given to the University of Wisconsin by the NOAA/NESDIS group resident at the University. The HIRS Cloud Analysis runs daily at Wisconsin using code developed by the Principal Investigator. The HIRS (High resolution Infrared Sounder) has four channels from 13 to 15 microns wavelength. These data are taken for deriving temperature soundings (vertical temperature structure) of remote areas of the Earth where conventional data from balloon borne systems are not available. The same channels also are used for accurately distinguishing cirrus clouds in the data processing at Wisconsin. The unique features of these data with respect to cirrus clouds are: 1) cirrus cloud detection is not dependent on sun light as the ISCCP, 2) the highly varying solar reflectance of the earth's surface does not have to be measured, 3) the combination of points 1 and 2 make this method of cirrus detection more sensitive than the ISCCP, 4) the infrared channels are minimally hampered by the large diurnal cycle in surface temperature, 5) the same sensors provide nearly uniform global coverage, and 6) monitoring of cloud changes in time is possible because these are operational sensors that NOAA will fly for the next decade. With the global HIRS data set that has spanned 9 years, relationships of cirrus clouds to other weather and climate parameters can be studied. Numerical modeling groups have just begun to look at these data to evaluate how well their models develop clouds globally. Studies of the relationship of clouds to weather and other atmospheric processes have just begun. Summaries of part of the HIRS Cloud Analysis are made available via the Principal Investigator's web page at <http://www.ssec.wisc.edu/~donw>.

The University of Wisconsin also operates a large data system called the McIDAS (Man computer Interactive Data Access System) which makes most of the data needed for weather forecasting, available to meteorologists. The McIDAS routinely acquires all of the data from the operational weather satellites along with conventional weather data from airports and balloon sounding

systems. The forecast fields from numerical models also are acquired by McIDAS and displayed in combination with the other satellite and weather data. The satellite data for SUCCESS and FIRE/ACE were taken from the McIDAS system. NASA Langley (Dr. P. Minnis) archived most of the data, however, the Principal Investigator at Wisconsin (Dr. Wylie) archived satellite data in the arctic for the periods when NASA Langley was not operating.

The Principal Investigator assembled all satellite and weather data and all model forecasts of the arctic basin into displays on one web page for the FIRE/ACE flights. These data were also used by the SHEBA Project Office and transmitted to the SHEBA ship in the arctic for planning their operations.

TASKS COMPLETED

- A) Weather forecasts were made for SUCCESS and FIRE/ACE flights. FIRE/ACE was the longest experiment the Principal Investigator participated in, over four months. Forecasts were made for the Canadian flights in April, 1998, before the FIRE/ACE Project Office opened in Fairbanks, Alaska. They were continued through May into June after the Project Office temporarily closed because the University of Washington was flying out of Barrow Alaska. In July the Principal Investigator returned to Fairbanks to support the second round of FIRE/ACE flights. Forecasts were made for about 105 days.
- B) Weather summaries were written for each day of aircraft operation. Data showing the areal extent of clouds and weather patterns were collected into daily summaries. Fifty four days are shown on the Principal Investigator's web page (<http://www.ssec.wisc.edu/~donw>).
- C) Back trajectory analyses of air to the areas studied by the aircraft in FIRE/ACE were made immediately after the experiment. This task was not originally proposed before FIRE/ACE. However, during the experiment, the studies of condensation nuclei raised questions about the sources of these particles. Previous studies made by the University of Alaska also pointed toward pollution of the arctic from European sources. The Principal Investigator decided to make air trajectory analyses for this experiment for the needs of the condensation nuclei analyses and to investigate the prior claims of pollution and nuclei sources in the arctic. The data for these analyses were being routinely acquired and archived by the Principal Investigator from NOAA's Center for Environmental Prediction (NCEP) as part of his weather and cloud forecasting operation. Thus the air history trajectory analyses were made part of the weather and cloud summaries for the flight days.
- D) The global analysis of the frequency and optical properties of cirrus clouds has been on going for the last nine years. A paper summarizing these data will be printed by the J. of Climate in late 1998. From these data we have found that cirrus clouds are more frequent than reported by weather observers and by the International Satellite Cloud Climatology Project (ISCCP). They occur over 40% of the time globally with some areas of the tropics having cirrus clouds 80 to 100% of the time. Comparisons with the SAGE (Stratospheric Aerosol and Gas Experiment) satellite data indicate that very thin cirrus that cannot be detected with HIRS data are even more prevalent. From the HIRS data we found that the area averaged transmission of the earth's infrared data to space is about 40%. We also have found that cirrus clouds have been increasing slightly in the northern hemisphere. Detailed studies to pin point time trends in areas affected by industrial cities and aircraft will be made in the future.

FUTURE PLANS:

- 1) Write a paper discussing how relevant the FIRE/ACE data are to the western part of the arctic basin. The FIRE/ACE weather, clouds, and air historical trajectories will be compared to past studies of this area in the literature.
- 2) Examine the HIRS Cloud Analysis data in finer detail to evaluate trends in areas affected by industry and aircraft.
- 3) Gather more climate scale information on radiative properties of clouds through inter-comparing cloud radiative data from the other satellite cloud climatologies, the ISCCP and SAGE, with the HIRS data.

RESULTS:

- A) The pressure and wind patterns forecasts by the NOAA's National Center for Environmental Prediction (NCEP) global model (MRF) were qualitatively accurate in the arctic basin. Tracks of storms, fronts and high pressure systems also seemed accurate to the forecaster (the Principal Investigator). Cloud forecasts are not part of the numerical system and were added by the Principal Investigator. Two cases were found where the European Center for Medium Range Forecasting (ECMWF) missed major low pressure centers for one day while NCEP correctly depicted these centers. This came as a surprise because of the highly acclaimed reputation of the ECMWF model in the weather forecasting community.
- B) Most of the air sampled during the FIRE/ACE flights came from the south and southeast, the Pacific Ocean across Alaska, or from northwestern Canada. Very few cases were found where the air came from central Russia or Europe. This was a small surprise because of prior publicity accusing Europe of polluting the arctic. However, recent literature also suggests that European and Russian air enter the arctic only a small fraction of the time. However, many of the air historical trajectories show that the air circling around the arctic having a long residence time in the arctic basin so pollution that has entered the arctic, probably remains there.
- C) The FIRE/ACE probably found cloud conditions nearly typical of the arctic basin in spite of the El Nino - Southern Oscillation Event (ENSO) which produced excessive melting. The many encounters with alto-stratus clouds were not desired because the object of the radiative studies was to be low level arctic stratus clouds. However, our previous perception of the arctic may have ignored the high alto-stratus clouds because most observations came from ground observers. Satellite data need to be studied to evaluate the natural frequency of the higher clouds in relation to their common occurrence during the FIRE/ACE flights.
- D) Cirrus clouds are more prevalent than previously thought from other cloud studies. Their frequency averaged globally is over 40% of the time. In the tropics they are even more frequent with some areas have cirrus cover all of the time (100%) during convective seasons. This conclusion comes from the comparison of the HIRS data with other global studies, the ISCCP and SAGE.

- E) When very thin clouds are included, the tropics are covered with some cloud nearly all of the time. Temperate latitudes also have more cloud cover than previously perceived.
- F) Cirrus clouds transmit about 40% of the earth's infrared radiation (areal average) and absorb and re-emit about 60%.
- G) Cirrus clouds are increasing at a slow rate in the northern hemisphere, about 0.5% per year.

Name: Donald Wylie
Institution: University of Wisconsin-Madison

SIGNIFICANT HIGHLIGHTS:

The most significant accomplishment of this work is that some evidence of cloud cover changes in time have been found in the HIRS data. The time trend of cloud cover is small, about 0.5% per year, but appears to be occurring. Details are given in the Figure below and in Wylie and Menzel, 1994: Eight Years of High Cloud Statistics Using HIRS, to be published in the Journal of Climate. These data have been carefully scrutinized for problems caused by sensor scan angle and changes in the solar time of the orbits of the satellites. The trends are small.

In the southern hemisphere, a trend is not distinguishable from larger annual and interannual variations. The annual cycle also intensifies in the southern hemisphere starting in 1991.

FREQUENCY OF CLOUD DETECTION OVER OCEANS

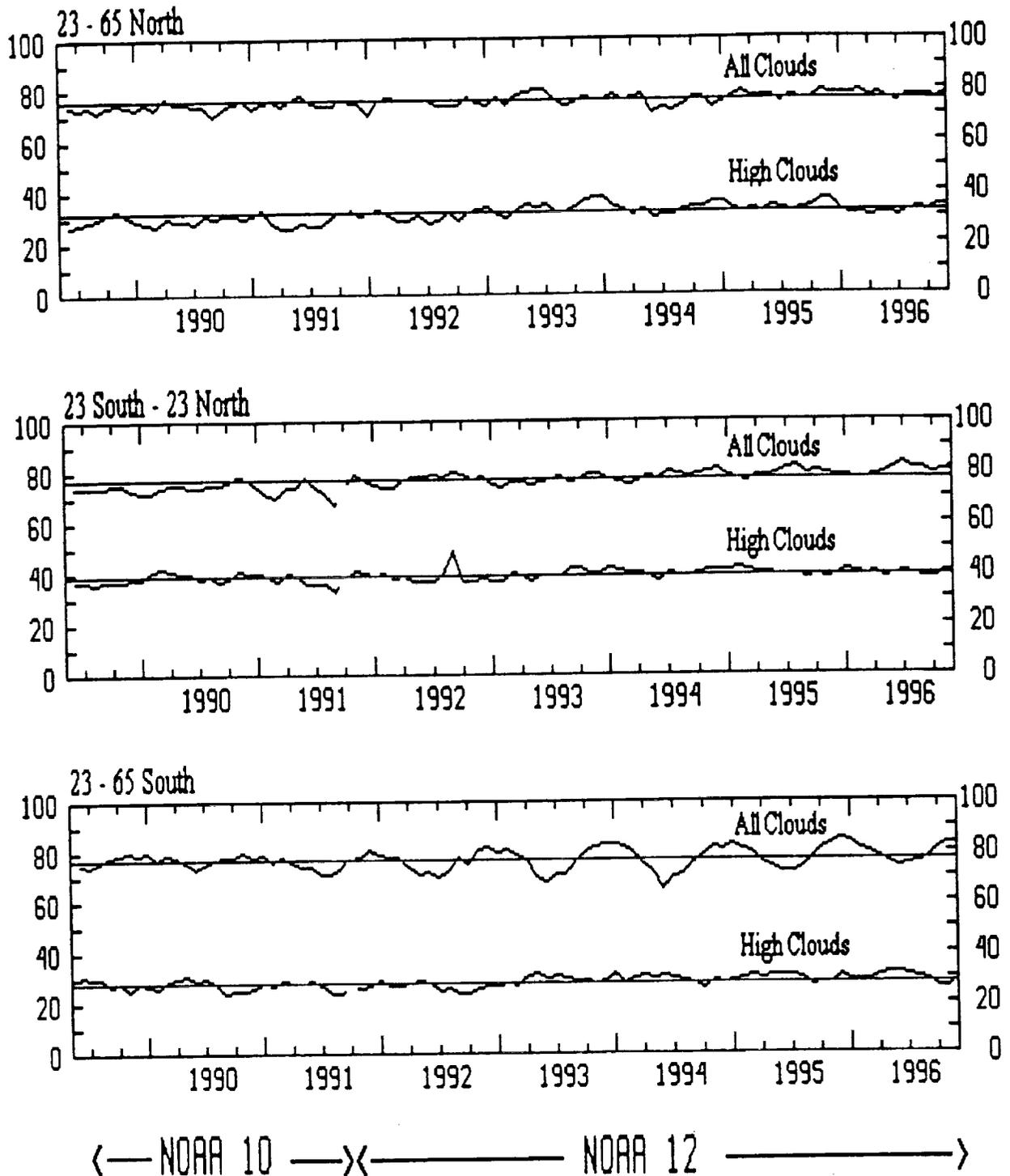


Figure: The cloud frequencies over water for sunrise and sunset satellites NOAA 10 and 12. Note that the Frequency of High Clouds (above 6 km) increase about 4% in eight years in the 23-65 north latitude belt (top panel) while a similar increase in All Clouds occurred in the tropics (middle panel). The annual cycle also increase in the bottom panel.

A second significant point is the applicability of the FIRE/ACE flights to the climate of the arctic basin. An example of the air trajectory analyses to the SHEBA ship for all of the flights in May is shown in the Figure below. The ship was located at about 76 north latitude and 165 west longitude during the month. The trajectories of air reaching the ship at 1.0 km altitude are shown. Most of the trajectories curve around the Beaufort Sea to the east of the SHEBA ship or come in a curved path from the north or west. A few came from the south across Alaska. None came from Europe or Russia. Some of the higher altitude trajectories can be traced back to Europe and Russia. But the lower level air mostly came from the arctic basin. This figure shows that the FIRE/ACE flights were sampling air with a long residence time in the arctic on most of the flights.

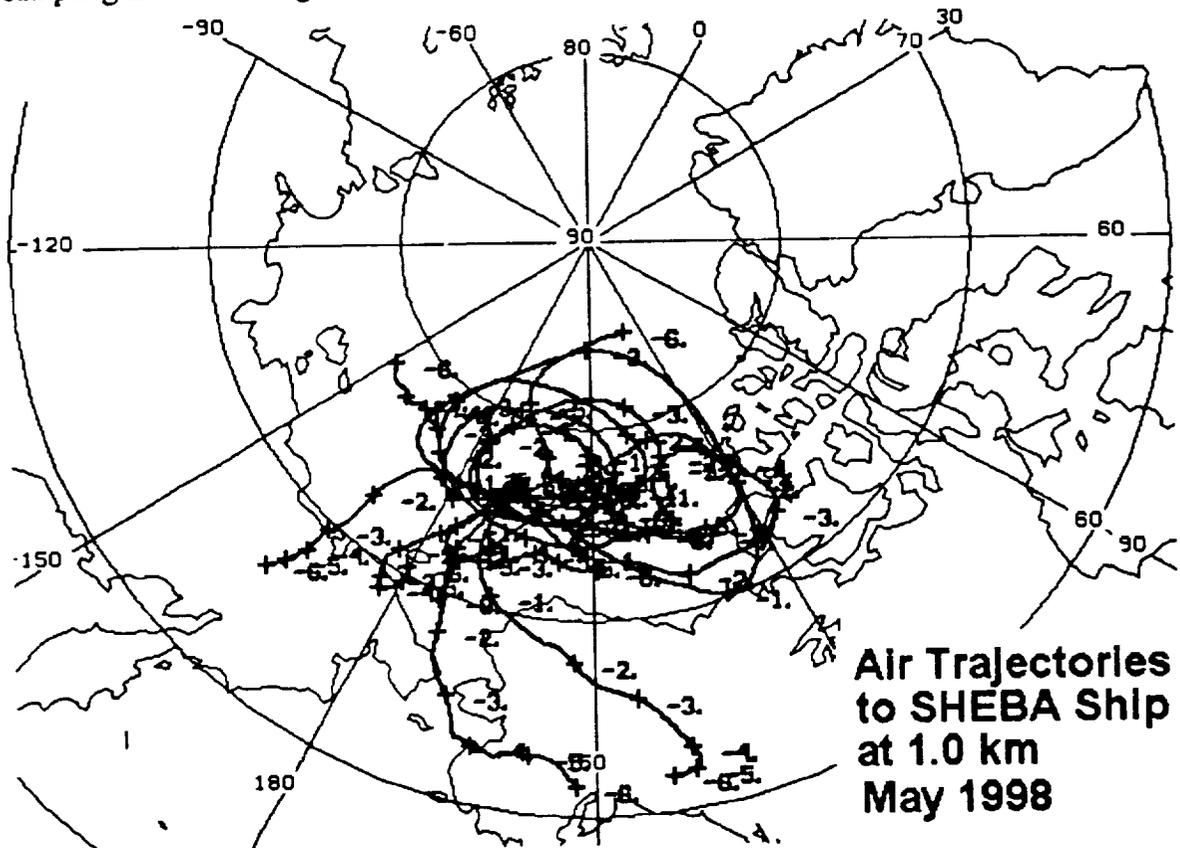


Figure: Summary of all air trajectories reaching the SHEBA ship over 6 days at one km altitude in the month of May 1998, during the flights of the C-130 and the ER-2.

Name: Donald Wylie
Institution: University of Wisconsin-Madison

FUTURE PLANS:

I would like to finish a publication on clouds, weather and air trajectories in the experiment focusing on what the cloud forms sampled during the experiment were, were they representative of the arctic, why were the cloud forms present, and were we sampling air typical of the arctic or an anomaly of a season or the ENSO? The ACE Objects call for a "test data set to support Arctic FIRE cloud modeling efforts." and "Why are these particular clouds produced in the Arctic." We need to know how typical the flight data are of arctic clouds and air in this region. This work has been started with my weather and air trajectory summaries on my web page. The daily discussions on the web page are brief and do not address the issue of how the FIRE/ACE data represent typical conditions in the arctic.

As we left Fairbanks we noted that a lot of the flights encountered alto-stratus clouds which were not expected before the experiment. How do we know what the common clouds of the arctic are? Does our impression of the arctic come from ground observations? If so, then it is biased by the clouds closest to the observer and often obscured by poor visibility. I have a 9 year data set from the HIRS satellite data. In my previous publications I ignored the arctic because of problems with finding clouds in the inversion and the temperature sounding from NCEP which I used in the analysis. The HIRS data have been taken and analyzed. Some corrections for recognizing misclassifications caused by the inversion could be made. The alto-stratus clouds, however, will easily be recognized in the HIRS data because they occurred above the inversion and will not require a correction. Cirrus also were present and were recognized in the HIRS analysis. The satellite data can describe cloud conditions of the middle and upper troposphere with out any adjustments. Some of the low level clouds too could be identified by tuning the algorithm to the arctic, which has not been done.

I propose a 1/2 man-year effort that will have two primary tasks:

- 1) Write a paper summarizing the weather, cloud, and air trajectories of the FIRE/ACE flights focusing on which days represent the more typical arctic conditions and which are rare in the region. I have collected some of the literature on weather and air trajectories in the arctic and have made the trajectory computations. Most of the computing is done. The reading and thinking remains.
- 2) Summarize the HIRS Cloud Analysis in the arctic to show what the frequencies of cloud forms are and show how common each flight's clouds and weather were to the arctic.

This work should take one year. Some collaboration may occur with other investigators such as the Condensation Nuclei investigators. I would like to assist these investigators in finding reasons or sources for the nuclei they found. Collaboration with radiative studies is also possible because the HIRS will show cirrus clouds above the flight level that were not sampled in the aircraft data. Quantitative optical depths of these clouds can be obtained from the HIRS data.

BUDGET

Budget will be about \$40,000 for one year. I'll send the proper proposal through the University in about two weeks.

Name: Donald Wylie
Institution: University of Wisconsin-Madison

All of the images I have produced are on my web page which is linked to the FIRE/ACE web page. I will transfer these data to the Langley DAAC in the future. I have two forms of data which may be useful to FIRE investigators, but only if they have a McIDAS. I have NOAA satellite images and the wind, temperature, and humidity analysis from NOAA NCEP. However, these data are held in a binary form readable only by McIDAS code. Images have been made from them and are displayed on my web page. If investigators want more data other than what is on the web page, images can be made for them on McIDAS. Since the only heavily used McIDAS systems are at Wisconsin and NASA Langley, I don't see a need to transfer the McIDAS formatted data to the DAAC. I have transferred satellite images to Minnis' group for displaying flight tracks. They have a McIDAS and are able to use the data.

Name: Donald Wylie

Institution: University of Wisconsin-Madison

BIBLIOGRAPHY:

Refereed Publications during FIRE-III.

- Wylie, D. P., and W. P. Menzel, 1998: Eight years of cloud statistics using HIRS., *J. Climate*, in press.
- Wylie, D. P., D. Santek, and D. O'C. Starr: 1998: Cloud-top heights from GOES-8 and GOES-9 stereoscopic imagery., *J. Appl. Meteor.*, **37**, 405-413.
- Wylie, D. P., and P. H. Wang, 1997: Comparison of cloud frequency data from the high-resolution infrared radiometer sounder and the Stratospheric Aerosol and Gas Experiment-II., *J. Geoph. Res.*, **102**, D25, 29,893-29,900.

Other FIRE Publications.

- Jin, Y., W. B. Rossow and Donald Wylie, 1996: Comparison of the climatologies of high-level clouds from HIRS and ISCCP., *J. Climate.*, **9**, 2850-2879.
- Wylie, D. P., P. Piironen, W. Wolf, and E. Eloranta, 1995: Understanding satellite cirrus cloud climatologies with calibrated lidar optical depths., *J.A.S.*, **52**, 4327-4343.
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- Menzel, W. P., T. J. Schmit, and D. P. Wylie, 1990: Cloud characteristics over central Amazonia during GTE/ABLE 2B derived from multispectral visible and infrared spin scan radiometer atmospheric sounder observations., *J. Geophys. Res.*, **95**, D10, 17,039-17,042.
- Starr, D. O'C., and D. P. Wylie, 1990: The 27-28 October 1986 FIRE cirrus case study: Meteorology and cloud fields. *Mon. Wea. Rev.*, **118**, 2259-2287.
- Wylie, D. P., B. B. Hinton, and K. Kloesel, 1989: *Mon. Wea. Rev.*, **117**, 2620-2625.
- Wylie, D.P., and W. P. Menzel, 1989: Two years of cloud cover statistics using VAS., *J. of Climate*, **2**, 380-392.

Recent Conference Report.

- Wylie, D. P., 1998: Clouds and Weather: A Satellite Perspective., Optical Society of America Topical Meeting on Cirrus., 6-8 October, Baltimore.

Name: Donald Wylie
Institution: University of Wisconsin-Madison

METRICS (do not include those in progress or planned):

- a. Number of publications (including books, book chapters, and refereed papers) - 4.
- b. Number of printed technical reports and non-refereed papers - 1.
- c. Number of oral or poster presentations at professional society meetings and conferences - 1.
- d. Number of citations of your publications (science citation index). ?
- e. Number of advance degree students: 0.
 - i. current
 - ii. graduated
- f. Number of post-doctorates - 0.
- g. Number and names of proposals: Only to NASA for this work.
 - i. submitted
 - ii. accepted
- h. Number of proposals and/or papers that you reviewed - 5.
- i. Number of committees served on (outside your organization) - 0.
- j. Number of patents (granted and applications) - 0.
- k. Number and names of honors and awards - 0.